The Study of Maximum Loading Point in Investigation of Capacitor Performance with Power Electronic Shunt Devices

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Abstract

One of the major causes of voltage instability is the reactive power limit of the system. Improving the system's reactive power handling capacity via Flexible AC transmission System (FACTS) devices is a remedy for prevention of voltage instability and hence voltage collapse. In this paper, the effects of Shunt Capacitor, SVC and STATCOM in Static Voltage Stability Margin Enhancement will be studied. The continuation power flow methods are proposed in case of the increasing loading of contingency. The IEEE-14 bus system is simulated to test the increasing loadability. It is found that these devices significantly increase the loadability margin of power systems.

1. Introduction

In recent years, the increase in peak load demand and power transfers between utilities has elevated concerns about system voltage security. Voltage collapse has been deemed responsible for several major disturbances and significant research efforts are under way in an effort to further understand voltage phenomena. A large portion of this research is concentrated on the steady state aspects of voltage stability. Indeed, numerous authors have proposed voltage stability indexes based upon some type of power flow analysis. A particular docility being encountered in such research is that the Jacobian of a Newton-Raphson power flow becomes singular at the steady state voltage stability limit. In fact, this stability limit, also called the critical point, is often defined as the point where the power flow Jacobian is singular. As a consequence, attempts at power flow solutions near the critical point are prone to divergence and error. For this reason, double precision computation and anti divergence algorithms have been used in attempts to overcome the numerical instability [1].

Voltage instability is mainly associated with reactive power imbalance. The loadability of a bus in the power system depends on the reactive power support that the bus can receive from the system as the system approaches the Maximum Loading Point (MLP) or voltage collapse point, both real and reactive power losses increase rapidly. Therefore, the reactive power supports have to be local and adequate.

Reactive power support can be done with FACTS devices. Each FACTS device has different characteristics; some of them may be problematic as far as the static voltage stability is concerned. Providing adequate reactive power support at the appropriate location solves voltage instability problems. There are many reactive compensation devices utilized by the utilities for this purpose, each of them has its own characteristics and limitations. However, from the utility point of view it would be good if they can achieve this with the most beneficial compensation device. Hence, in the paper, an effort is made to compare the advantages and disadvantages of currently available and the most commonly used shunt-compensation devices.

Rest of the paper is organized as follows: Section 2 introduces static voltage stability in general. A brief introduction of shunt capacitor and the stability models including AC and DC representations of SVC and STATCOM is presented in Section 3. Section 4 is depicted to simulation of static voltage stability on IEEE 14 bus test system with implementing SVC and STATCOM. Section 5 reviews the main points discussed this paper.

2. Static Voltage Stability

In static voltage stability, slowly developing changes in the power system occur that eventually lead to a shortage of reactive power and declining voltage. Voltage collapse phenomena in power systems have become one of the important concerns in the power industry over the last two decades, as this has been the major reason for several major blackouts that have occurred throughout the world including the recent Northeast Power outage in North America in August 2003 [2]. Point of collapse method and continuation method are used for voltage collapse studies [3]. Of these two techniques continuation power flow method is used for voltage analysis. These techniques involve the identification of the system equilibrium points or voltage collapse points where the related power flow Jacobian becomes singular [4, 5]. The only way to save the system from voltage collapse is to reduce the reactive power load or add additional reactive power prior to reaching the point of voltage collapse [6].

Usually, placing adequate reactive power support at the "weakest bus" enhances static-voltage stability margins. The weakest bus is defined as the bus, which is nearest to experiencing a voltage collapse. Equivalently, the weakest bus is one that has a large ratio of differential change in voltage to differential change in load ($\partial V / \partial P_{Total}$). Changes in voltage at each bus for a given change in system load are available from the tangent vector, which can be readily obtained from the predictor steps in the CPF process. In addition to the above method, the weakest bus could be obtained by looking at right eigenvectors associated with the smallest eigenvalue as well.

Using reformulated power flow equations, the differential change in the system active power is:

$$dP_{total} = Cd\lambda \qquad (1)$$

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Thus the weakest bus would be:

$$BUS = \max\left\{ \left|\frac{dV_1}{Cd\lambda}\right|, \left|\frac{dV_2}{Cd\lambda}\right|, \dots, \left|\frac{dV_n}{Cd\lambda}\right| \right\} \quad (2)$$

Since the value of $Cd\lambda$ is the same for each dV elements in given tangent vector, choosing the weakest bus is as easy as choosing the bus with largest dV component. In addition to the above method weakest bus could be obtained by looking at the right eigenvectors associated with the smallest eigenvalue as well.

3. Shunt Capacitor, SVC and STATCOM

It is well-know fact that shunt compensation can be used to provide reactive power compensation. Traditional shunt capacitors or newly introduced FACTS controllers can be used for this purpose. FACTS controllers are very expensive; References [7, 8] give an idea about the cost of various shunt controllers. Description of each of these controllers, along with their terminal characteristics is given in the next subsections.

2.1. Shunt Capacitor

Shunt capacitors are relatively inexpensive to install and maintain. Installing the shunt capacitors in the load area or the point that they are needed will increase the voltage stability. However, shunt capacitor have the problem of poor voltage regulation and beyond a certain level of compensation a stable operating point is unattainable.

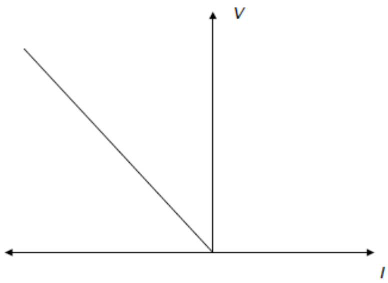

Fig. 1. Terminal characteristic of shunt capacitor

Furthermore, the reactive power delivered by the shunt capacitor is proportional to the square of the terminal voltage; during the low voltage conditions the var support drops thus computing the problem [9]. The characteristic of shunt capacitor can be shown in the Fig. 1.

2.2. Static Var Compensator (SVC)

SVC is a shunt connected static var generator/load whose output is adjusted to exchange capacitive or inductive current so as to maintain or control specific power system variable. Assuming controller voltage equal to the bus voltage and performing a Fourier series analysis on the inductor current wave form, the TCR at fundamental frequency can be considered to act like variable inductance given by [9,10]:

$$X_V = X_L \frac{\pi}{2(\pi - \alpha) + \sin 2\alpha} \quad (3)$$

Where, X_L is the reactance caused by the fundamental frequency without thyristor control and α is the firing angle, hence, the total equivalent impedance of the controller can be represented as:

$$X_e = X_c \frac{\pi / r_x}{\sin 2\alpha - 2\alpha + \pi(2 - \frac{1}{r_x})} \quad (4)$$

Where $r_x = X_C / X_L$, the limits of the controller are given by the firing angle limits, which are fixed by design. The typical steady-state control law of a SVC used here is depicted in Fig. 2, and may be represented by the following voltage-current characteristic:

$$V = V_{ref} + X_{SL} I \quad (5)$$

Where V and I stand for the total controller RMS voltage and current magnitudes, respectively, and V_{ref} represents a reference voltage.

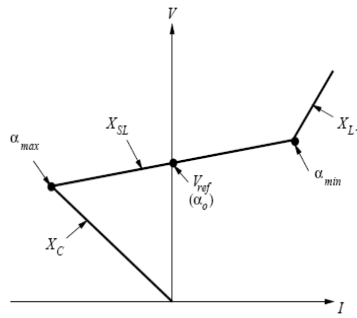

Fig. 2. Typical steady state V–I characteristic of a SVC

Typical values for the slope X_{SL} are in the range of 2 to 5%, with respect to the SVC base; this is needed to avoid hitting limits for small variations of the bus voltage. A typical value for the controlled voltage range is ±5% about V_{ref} [11]. At the firing angle limits, the SVC is transformed into a fixed reactance.

2.3. Static Synchronous Compensator (STATCOM)

STATCOM is the Voltage-Source Inverter (VSI), which converts a DC input voltage into AC output voltage in order to compensate the active and reactive power needed by the system [12]. From Fig. 3, STATCOM exhibits constant current characteristics when the voltage is low/high under/over the limit. This allows STATCOM to delivers constant reactive power at the limits compared to SVC.

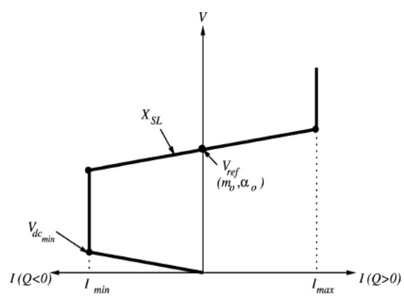

Fig. 3. Typical steady state V–I characteristic of a STATCOM

The AC circuit is considered in steady-state, whereas the DC circuit is described by the following differential equation, in terms of the voltage V_{dc} on the capacitor [10, 13]:

$$V_{dc} = \frac{P}{CV_{dc}} - \frac{V_{dc}}{R_c C} - \frac{R(P^2+Q^2)}{CV^2 V_{de}} \qquad (6)$$

The power injection at the AC bus has the form:

$$P = V^2 G - KV_{dc}VG\cos(\theta-\alpha) - KV_{dc}VB\sin(\theta-\alpha) \qquad (7)$$

$$Q = V^2 B - KV_{dc}VB\cos(\theta-\alpha) - KV_{dc}VG\sin(\theta-\alpha) \qquad (8)$$

Where $k = \sqrt{3/8m}$.

4. Simulation Results

A IEEE 14-bus test system as shown in Fig. 4 is used for voltage stability studies. The test system consists of five generators and eleven PQ bus (or load bus). The simulations use PSAT simulation software [14, 15]. PSAT is power system analysis software, which has many features including power flow and continuation power flow. Using continuation power flow feature of PSAT, voltage stability of the test system is investigated.

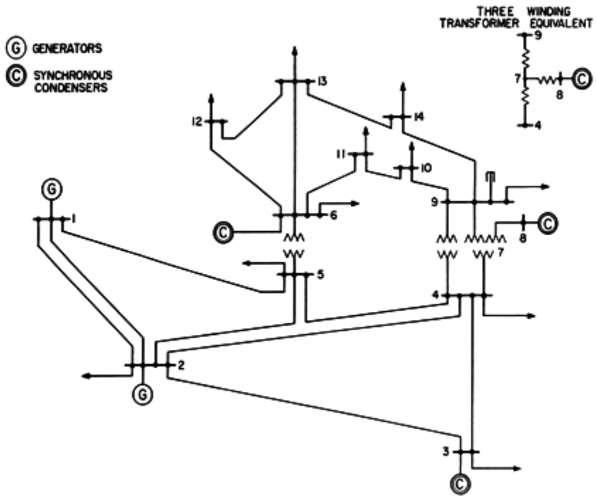

Fig. 4. The IEEE 14-bus test system

The behavior of the test system with and without shunt compensation devices under different loading conditions is studied. The location of the shunt compensation devices is determined through bifurcation analysis. A typical PQ model is used for the loads and the generator limits are ignored. Voltage stability analysis is performed by starting from an initial stable operating point and then increasing the loads by a factor λ until singular point of power flow linearization is reached.

In this study, in order to obtain the P-V curves hence the loading margin of the system for different cases, all the loads were represented as constant PQ and increased according to (9), i.e. keeping constant power factor.

$$P_L = P_{L0}(1+\lambda)$$
$$Q_L = Q_{L0}(1+\lambda) \qquad (9)$$

Where P_{L0} and Q_{L0} are the active and reactive base loads, whereas P_L , and Q_L , are the active and reactive loads at bus L for the current operating point as defined by λ .

From the continuation power flow results which are shown in the Fig. 5, the buses 4, 5, 9 and 14 are the critical buses. Among these buses, bus 14 has the weakest voltage profile. Fig. 6 shows PV curves for 14-bus test system without shunt compensation devices. The system presents a collapse or Maximum Loading Point, where the system Jacobian matrix become singular at $\lambda_{\max} = 3.97295$ p.u. Based on largest entries in the right and left eigenvectors associated to the zero eigenvalue at the collapse point, bus 14 is indicated as the "critical voltage bus" needing Q support. Voltage magnitude in MLP in bus 14 that is known as the weakest bus is 0.68833 p.u.

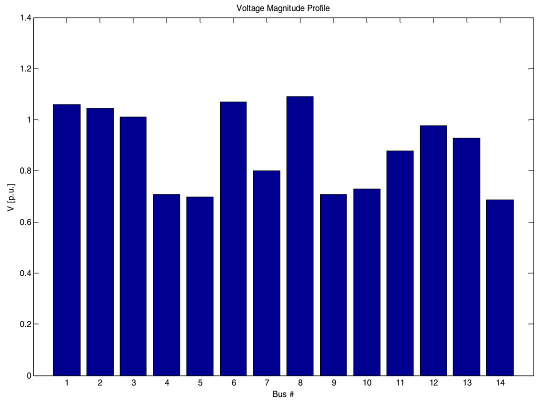

Fig. 5. Voltage magnitude profile for 14-bus test system without shunt compensation devices

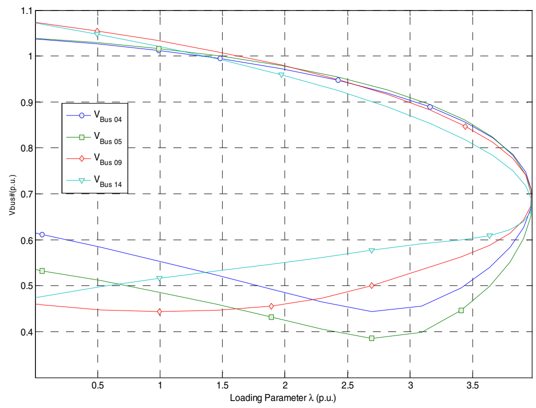

Fig. 6. PV curves for 14-bus test system without shunt compensation devices

In order to get a rough estimate of reactive power support needed at the weakest bus and corresponding loading margin for a given load and generation direction, a synchronous compensator with no limit on reactive power was used at the weakest bus. Based on collapse analysis bus 14 is targeted as the first location for a Shunt Capacitor. PV curves at the weakest bus with Shunt Capacitor are given in Fig. 7.

As can be seen from the P-V curves, Shunt Capacitor improves the static voltage stability margin of the system. The new maximum loading level in this condition is $\lambda_{\max} = 4.03258$p.u.

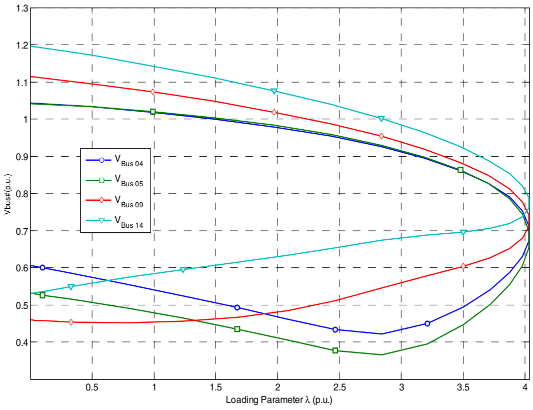

Fig. 7. PV curves for 14-bus test system with Shunt Capacitor

Next, remove the Shunt Capacitor, and insert the SVC at bus 14 and then repeat to create PV curve again. The results of locating the SVC at the desired bus are depicted in the voltage profile of Fig. 8. The new maximum loading level in this condition is $\lambda_{\max} = 4.08238$ p.u.

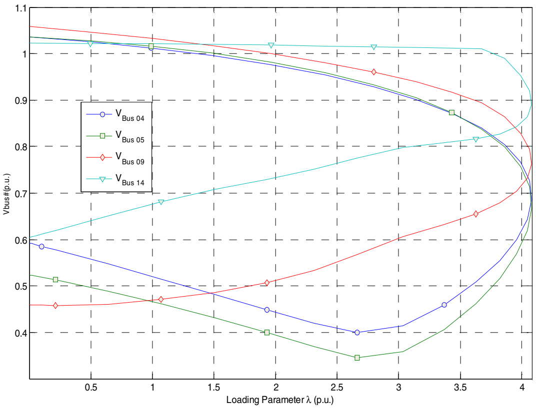

Fig. 8. PV curves for 14-bus test system with SVC

Then, remove the SVC, and insert the STATCOM at the bus 14 which the lowest the critical point and repeat the simulation. When STATCOM is connected at bus 14, we can observe from Fig. 9 that bus 14 has a flatter voltage profile. The Maximum Loading Point is increasing further at $\lambda_{\max} = 4.0892$ p.u. It is noticed that bus 5 is the next weakest bus if the STATCOM is introduced at bus 14.

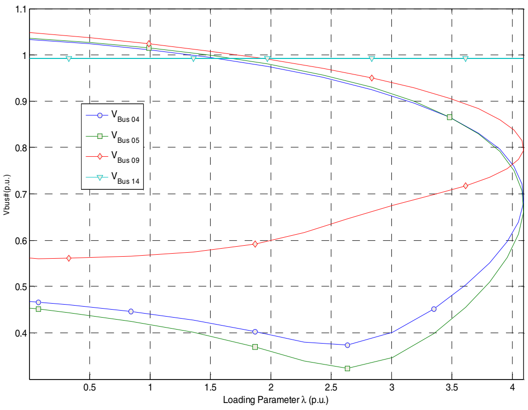

Fig. 9. PV curves for 14-bus test system with STATCOM

PV curves at the weakest bus of Base Case, with various shunt compensation devices are given in Fig. 10. As can be seen from the P-V curves, all the devices improve the static voltage stability margin of the system; however, the voltage level of the weakest bus for shunt capacitor at the lightly loaded condition is not acceptable-too high. SVC and STACOM, the voltage profile is in the acceptable range even for a higher loading point as expected.

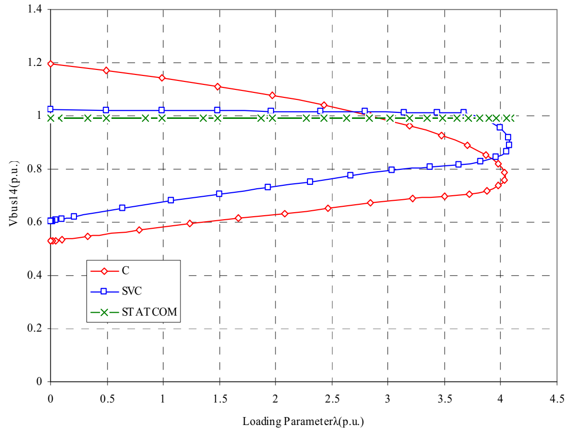

Fig. 10. PV curves for bus 14 with various shunt controllers

A snap shot of voltage profile at all the busses with different controllers are given in Fig. 11 at the maximum loading point. The shunt capacitors can be used to increase the voltage stability of the system by moving the nose point of PV curve out and up. However, due to the very rapid decline of the voltage near the nose point, the best warning signal by the gradual decline in the system voltage is taken away. The shunt capacitor cannot be gradually connected because there is no warning to the system operator for the coming of the collapse point. Using of SVC and STATCOM give the view of voltage decline before entering to the collapse point.

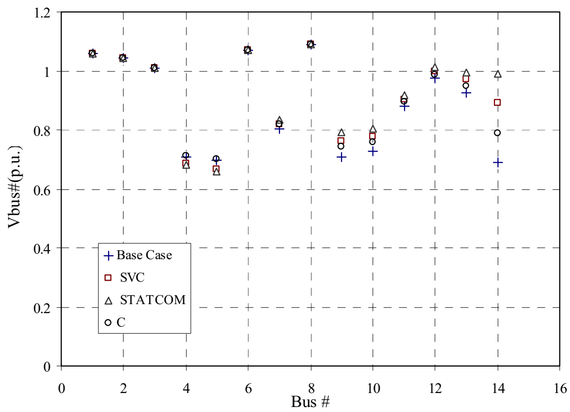

Fig. 11. Voltage profile of each bus at the MLP for different shunt controllers

The SVC and STATCOM significantly affects the shape of the PV curve, which improves the critical point without masking the nose point by only shift out the PV curve. The use of shunt capacitor might lead to the unacceptable voltage magnitude in normal operation, and the amount of reactive power delivered is mostly dependent on the voltage magnitude. Hence, it makes the power transfer ability to extend but could not be the main use to improve voltage stability.

The SVC and STATCOM can do a much better job with the improvement of voltage stability while keeping the voltage in the acceptable region. At first that system experiences light load, the voltage profile of this bus with SVC and STATCOM is the same. In this condition SVC and STATCOM operate in linear region of their V-I characteristics. When the load of the system is increased, the effect of STATCOM in improving the voltage is more adequate than the SVC. When the maximum limit is reached, the SVC behaves exactly like a fixed shunt capacitor. The values of λ_{max} with all types of shunt compensation devices are compared in Table 1. From the table, it is obvious that STATCOM gives the maximum loading margin compared to other devices.

Table 1. Maximum Loading Point with all types of shunt compensation devices

	Base Case	C	SVC	STATCOM
λ_{max} (p.u.)	3.973	4.032	4.082	4.089

In maximum load condition or MLP, the magnitude of the bus no.14 voltage reaches to 0.78825 (with C) and reaches to 0.88987 p.u. (with SVC) and reaches to 0.99237 p.u. (with STATCOM) from 0.68833 p.u. (Base Case).

5. Conclusions

A comparison study of shunt-capacitor, SVC and STATCOM in static voltage stability margin enhancement is presented. Various merits and demerits of the shunt compensation devices are discussed in details. Shunt Capacitor, SVC and STATCOM increase static voltage stability margin and power transfer capability. However, SVC and STACOM pose a better behavior in loss reduction and voltage profile. The increase in losses in the shunt capacitor at the lightly loaded conditions is due to poor voltage profile. A remote voltage control scheme can be implemented to solve the voltage control problem at the shunt capacitor bus. The results of simulations also show that with the insertion of STATCOM, improving these parameters and steady-state stability of the system is more than the case when the SVC is inserted in the system. Overall SVC and STACOM behave better, however these controllers are expensive when compared to the shunt capacitor. A complete cost-benefit analysis has to be carried out in justifying the economic viability of the SVC and STATCOM.

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